NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

# WARTIME REPORT

ORIGINALLY ISSUED

August 1945 as
Advance Restricted Report E5F13

## STANDARD PROCEDURES FOR RATING AND TESTING CENTRIFUGAL COMPRESSORS

By NACA Subcommittee on Supercharger Compressors

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WASHINGTON

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE RESTRICTED REPORT

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# CENTRIFUGAL COMPRESSORS

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## SUMMARY

The test-rig installation, measurements, instrumentation, test procedure, methods of calculation, and presentation of data, adopted by the National Advisory Committee for Aeronautics as standard for rating and testing centrifugal superchargers, are given in this paper.

## INTRODUCTION

The original version of this report was released in February 1942 and the present revision is the first one issued since that date. The membership of the Subcommittee on Supercharger Compressors, who have sponsored this paper, is as follows:

Mr. Kenneth Campbell, chairman
Mr. Rudolph Birmann
Lt. Comdr. William Bollay, U.S.N.R.
Mr. Opie Chenoweth
Mr. Walter Doll
Professor Howard W. Emmons
Commander W. T. Hines, U.S.N.
Lt. Comdr. John Marchant, U.S.N.R.
Mr. Arnold H. Redding
Mr. Oscar W. Schey
Mr. John Stack
Mr. John Talbert
Mr. W. S. Thompson

The present report, which supersedes the one bearing essentially the same title and dated February 1942, has been made to conform with the recently compiled method of graphical presentation (reference 1).

## RÉSUMÉ

The testing of a centrifugal supercharger requires a suitable installation to permit readings of true gas pressures and temperatures in the inlet and outlet of the supercharger in order to evaluate its performance. Tests are made at various impeller speeds, the volume of gas flow being varied from full throttle to pulsation for each speed.

Reference 2 enumerates the bases for most of the procedure, lists alternative procedures, and suggests where caution is most required in conducting the tests.

## TEST-RIG INSTALLATION

The rig used to test the combination of impeller, diffuser, collector case, and housing of a centrifugal supercharger should be provided with inlet and outlet pipes of such length that true pressures and temperatures can be obtained, a means for measuring the quantity of air passing through the supercharger, throttle valves for regulating the volume flow and the gas pressures in the inlet and discharge of the supercharger, and a driving mechanism for the supercharger.

In detail, the installation shall include:

(a) An air-measuring apparatus at the entrance or exit to the system.

(b) A throttle valve ahead of a straight inlet duct.

(c) A straight inlet duct of the same constant cross-section shape and area as the compressor inlet opening, the duct to have a length at least 15 times its smallest crosswise dimension. The compressor inlet may be an axial inlet connection or the connection to a conventional inlet elbow, depending on the nature and purpose of the test setup.

(d) A rear assembly without the carburetor.

(e) Straight discharge stacks at least 15 diameters long. It may be unnecessary to install discharge stacks in all radial-engine outlet ports, but a symmetrical arrangement should be used. Any ports not connected with stacks should be plugged. The discharge stack for any type of compressor shall be adequately lagged against heat transfer ahead of the station at which pressure and temperature

measurements are taken so that there will be no appreciable temperature drop. If the compressor is tested with any appreciable air movement over the compressor, the compressor should also be lagged. In presenting the results of an investigation, the report should state if the compressor is lagged as well as the amount and type of lagging used. The discharge stacks shall lead into a low-resistance collector, the outlet of which contains a throttle valve for use in varying the discharge pressures.

## MEASUREMENTS

During one test the following measurements shall be taken: temperature of the air upstream of the air-measuring apparatus; pressure drop across the air-measuring apparatus; barometric pressure; total pressure, static pressure, and temperature in the inlet and in at least two outlet pipes (if more than one is used); supercharger speed; supercharger torque (if possible); static pressure at impeller entrance chamber (if such a chamber forms part of supercharger) and in the diffuser discharge collector (the purpose of these static pressures is to make possible correlation with engine operation if later desired); and wet and dry bulb readings (or the dew point).

Inlet measurements:

(a) One total pressure shall be measured in the stream at a distance equal to one-third of the distance across the duct in a plane located at a distance from the inlet flange of the supercharger housing equal to twice the smallest dimension of the cross section of the inlet duct.

(b) One static pressure shall be measured in the same plane in which the total pressure is measured.

(c) One static pressure shall be measured at the impeller entrance chamber, if any, on one side of the center line at right angles to the direction of air approach.

(d) Two temperatures shall be measured in the plane of the pressure measurements. The measurements shall be made at a distance of one-third of the duct width from the duct wall.

Outlet measurements:

(a) At least two total pressures shall be taken each 12 diameters from the discharge port flange of a discharge pipe (in at

least two separate pipes if installation calls for more than one pipe). The measurements shall be made one-third of the pipe diameter from the pipe walls and shall be so arranged with respect to pipe location that they represent the average pressure in all the pipes.

(b) Two static pressures shall be taken in the same pipes and in the same planes that the total pressures are taken.

(c) One static pressure in the diffuser discharge collector at the standard connection provided shall be taken.

(d) One temperature shall be measured in each discharge pipe and in the same plane in which the pressures are taken. The measurements shall be made one-third of the pipe diameter from the pipe walls.

The locations of pressure and temperature measurements in an inlet and an outlet pipe are shown in figure 1. Pressure readings shall be taken to 0.05 inch of mercury and temperature readings shall be taken to within $0.5^{\circ}$ F.

Air-volume measurements:

(a) The barometric pressure shall be obtained and corrected for temperature.

(b) The pressure drop across the measuring device shall be obtained, pressure taps to be located according to A.S.M.E. standards.

(c) The temperature of the air upstream of the measuring device shall be measured.

(d) The accuracy of the air-volume measurement shall be $\pm 1\frac{1}{2}$ percent.

Speed measurement:

(a) The speed of the supercharger shall be measured and maintained constant within ±1/2 percent.

Figures 2 and 3 are diagrammatic sketches of test rigs for inline and radial-engine superchargers, respectively. The positions at which measurements are taken are shown on the figures.

## INSTRUMENTS

Both thin-plate orifices and smooth-approach nozzles are generally used for the measurement of the gas volume. Gasometers are used by a few laboratories. Calibrated liquid-in-glass thermometers are used to obtain the temperature in front of the thin-plate orifices or nozzles and a micromanometer is used to measure the pressure difference across the orifice.

Total-pressure tubes shall be used to measure total pressures. They shall have slightly tapered tips and shall point directly upstream. The tubes shall have an outside diameter of 0.090 inch and an inside diameter of 0.040 inch. Pitot-static tubes with an outside diameter of 0.189 inch have also been found satisfactory when they are not too large in comparison with the duct in which they are placed. These tubes are shown in figure 4.

Static-pressure measurements shall be obtained either by means of wall-static tubes of from 0.020-inch to 0.040-inch inside diameter or by means of pitot-static tubes.

Mercury manometers shall be used in reading the pressures.

In supercharger testing, thermocouples have been found to be reliable and convenient temperature-measuring devices. Wires shall be of small diameter in order to reduce errors due to conduction along the leads. Each spool of wire shall be calibrated (see reference 3) for accurate results. Thermocouples of 34-gage (Brown & Sharpe Mfg. Co.) copper and 32-gage cupron wire are recommended. The thermocouples shall be inserted in brass sleeves approximately 3/32-inch outside diameter, the sleeves being brazed to nuts which shall be screwed into the walls of the pipes. (See fig. 4.)

The thermocouple cold junction shall be made such that the change of temperature of the junction is very slow. This slow change is accomplished by inserting the junctions in ice or in an insulated box or by attaching them to metal blocks of appreciable mass. More complete information on ice-bath cold junctions is given in reference 3. A potentiometer shall be used to obtain temperature readings.

Any speed-measuring apparatus that will give the accuracy of measurement which has been specified shall be used. Torque may be obtained by any suitable means, such as a dynamometer and a weighing scale (when a dynamometer is used as the driving unit).

## TEST PROCEDURE

Tests shall be made at equivalent tip speeds of 800, 1100, 1200, 1300, 1400, and 1500 feet per second and at higher speeds in increments of 100 feet per second until the limiting speed of the supercharger is reached. Other speeds shall be tested as required in order to bracket the operating range of the engine. For each constant speed, the volume flow shall be varied in a number of steps from full throttle to pulsation by means of the inlet and outlet throttle valves, and complete readings shall be taken at each setting thus obtained. Either inlet or outlet total pressure shall be held constant to within ±0.5 percent of the value of the absolute pressure.

Great care shall be taken in conducting the tests, particularly in regard to the following precautions:

(a) Adjust speed and throttle settings to hold engine speed and pressure values within the limits previously set forth.

(b) Wait 15 to 20 minutes for oil temperature to reach equilibrium after change in speed.

(c) Wait until air-out temperature stabilizes after each change of volume flow before readings are taken.

(d) Take a complete set of readings as rapidly as possible in an established sequence.

(e) The oil consumption due to leakage into the supercharger proper shall not exceed 5 pounds per hour.

## COMPUTATIONS AND PRESENTATION OF DATA

The true-stream and total temperatures shall be obtained from the observed data by the following formulas only if the airspeed exceeds 200 feet per second in the inlet pipe and 260 feet per second in the outlet pipe:

$$T_s = T_o \left(1 - 0.283\ \alpha \frac{\Delta p}{p_t}\right) \tag{1}$$

$$T_t = T_o \left[1 + 0.283\ (1 - \alpha) \frac{\Delta p}{p_t}\right] \tag{2}$$

A list of symbols is given in the appendix. The derivation of equations (1) and (2) is given in reference 2.

For speeds of less than 200 feet per second in the inlet pipe and 260 feet per second in the outlet pipe, the true-stream and total temperatures shall be assumed to be equal to the observed temperatures.

The supercharger performance shall be represented by curves of total-pressure ratio $p_{2t}/p_{1t}$, against corrected volume flow $Q_{1t}/\sqrt{\theta}$ with efficiency contours added; in certain cases curves of pressure coefficient $q_{ad}$, adiabatic efficiency $\eta_{ad}$, adiabatic shaft efficiency $\eta_s$ against load coefficient $Q_{1t}/n$ for each impeller speed are included. The method of plotting is illustrated in reference 1. The parameters shall be calculated as follows:

$$q_{ad} = \frac{6082\ T_{1t}}{V^2}\left[\left(\frac{p_{2t}}{p_{1t}}\right)^{0.283} - 1\right] \tag{3}$$

$$\eta_{ad} = \frac{T_{1t}\left[\left(\frac{p_{2t}}{p_{1t}}\right)^{0.283} - 1\right]}{T_{2t} - T_{1t}} \tag{4}$$

$$\eta_s = \frac{189.05\ W\ T_{1t}\left[\left(\frac{p_{2t}}{p_{1t}}\right)^{0.283} - 1\right]}{P} \tag{5}$$

$$Q_{1t} = \frac{0.7564\ W\ T_{1t}}{p_{1t}} \tag{6}$$

$$W = \frac{p_a\ Q_n}{53.50\ T_n} \tag{7}$$

The volume $Q_n$ shall be calculated from the orifice temperature and pressure drop according to methods given in reference 4.

The average velocity in the outlet pipes shall be computed at all speeds at the peak points of the efficiency curves from the weight of air flowing through the supercharger, the total cross-sectional area of the outlet pipes, and the mean density of the air in the outlet pipes at a position 12 diameters from the discharge port flanges of the supercharger.

Corrections shall be made to the supercharger parameter for a change of humidity greater than 55 grains per pound from that of normal air according to the formulas:

$$\text{Change in } q_{ad} = 0.000077\, q_{ad}\, (m - 36.5)$$

$$\text{Change in } \eta_{ad} = -0.000043\, \eta_{ad}\, (m - 36.5)$$

$$\text{Change in } \frac{Q_{1t}}{\sqrt{\theta}} = 0.000043\, \frac{Q_{1t}}{\sqrt{\theta}}\, (m - 36.5)$$

$$\text{Change in } \frac{Q_{1t}}{n} = 0.000043\, \frac{Q_{1t}}{n}\, (m - 36.5)$$

$$\text{Change in } \eta_s = 0.000034 \times \eta_s (m - 36.5)$$

$$\text{Change in } \frac{p_{2t}}{p_{1t}} = -0.00015 \left(\frac{Y}{1 + Y}\right)\left(\frac{p_{2t}}{p_{1t}}\right) (m - 36.5)$$

The significance of the various coefficients and efficiencies used is discussed in reference 2.

National Advisory Committee for Aeronautics,
Washington, D. C., June 13, 1945.

## APPENDIX - SYMBOLS

| | |
|---|---|
| $m$ | specific humidity, grains/lb |
| $n$ | angular velocity of impeller, rps |
| $P$ | net shaft power (gross shaft power minus friction power), ft-lb/sec |
| $p$ | pressure (obtained from corrected barometric pressure and pressure readings), in. Hg abs. |
| $p_a$ | corrected barometric pressure, total pressure of dry air and water vapor (corrected for temperature), lb/sq ft |
| $\theta$ | ratio of inlet stagnation temperature to standard sea-level temperature, $T_{1t}/518.4$ |
| $Q_{1t}$ | volume flow based on inlet stagnation conditions, cu ft/sec or cu ft/min as applied |
| $q_{ad}$ | pressure coefficient |
| $T$ | temperature, $^{\circ}$F abs. ($^{\circ}$F + 459.4) |
| $V$ | impeller tip speed, fps |
| $W$ | flow rate, lb/sec |
| $Y$ | $(p_{2t}/p_{1t})^{0.283} - 1$ |
| $\alpha$ | recovery coefficient of thermometric device |
| $\Delta p$ | kinetic pressure, in. Hg ($p_t - p_s$) |
| $\eta_{ad}$ | adiabatic temperature-rise ratio or adiabatic efficiency |
| $\eta_s$ | adiabatic shaft efficiency |
| $Q_{1t}/n$ | load coefficient, cu ft/impeller revolution |
| $Q_{1t}/\sqrt{\theta}$ | corrected volume flow, cu ft/min |

Subscripts:

| | |
|---|---|
| 1 | condition at inlet of supercharger |
| 2 | condition at outlet of supercharger |

n nozzle or orifice

o observed value

s static or true-stream value (except in symbol $\eta_s$)

t total or stagnation value

For example, $T_{1s}$ is the absolute static temperature of the air at the inlet of the supercharger.

## REFERENCES

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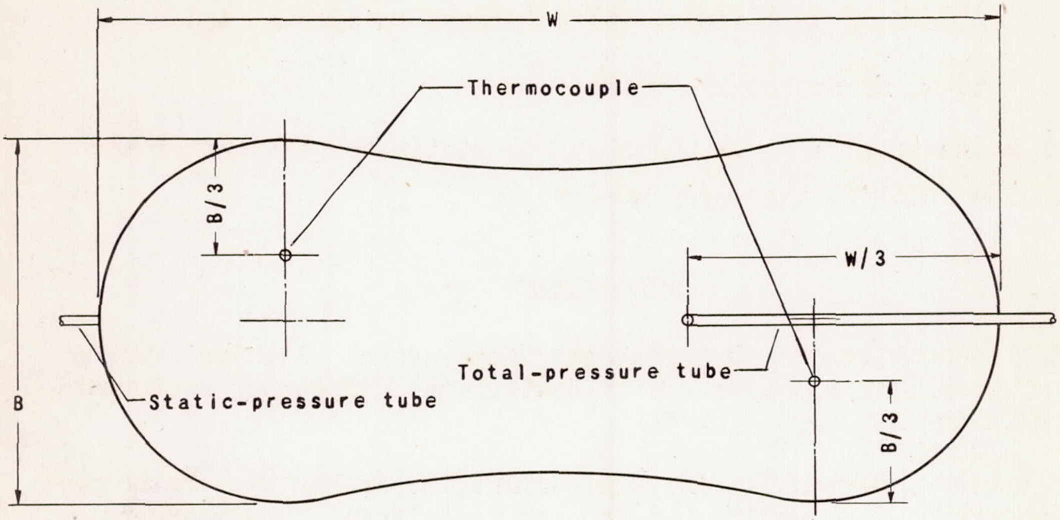
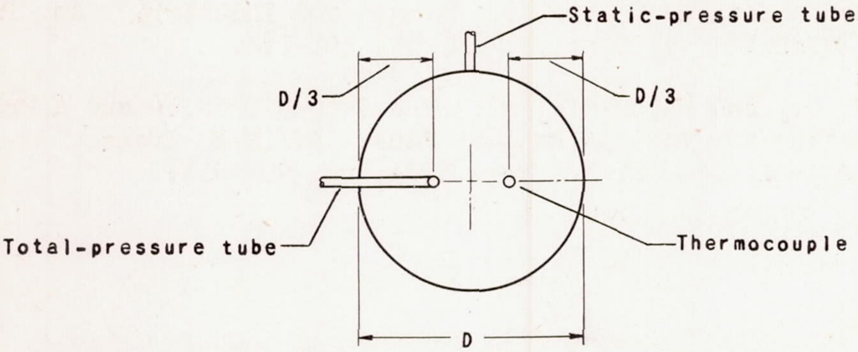
3. Roesser, Wm. F., and Wensel, H. T.: Methods of Testing Thermocouples and Thermocouple Materials. Ch. 2 of "Temperature - Its Measurement and Control in Science and Industry," Am. Inst. Phys., Reinhold Pub. Corp., 1941, pp. 291-292.

4. Ebaugh, N. C., and Whitfield, R.: The Intake Orifice and a Proposed Method for Testing Exhaust Fans. A.S.M.E. Trans., PTC-56-3, vol. 56, no. 12, Dec. 1934, pp. 903-911.




Typical inlet

Measurements at 2B from the inlet flange




Outlet

Measurements at 12 diam. from the outlet flange

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Figure 1. - Pressure and temperature measurement locations in pipe cross sections.

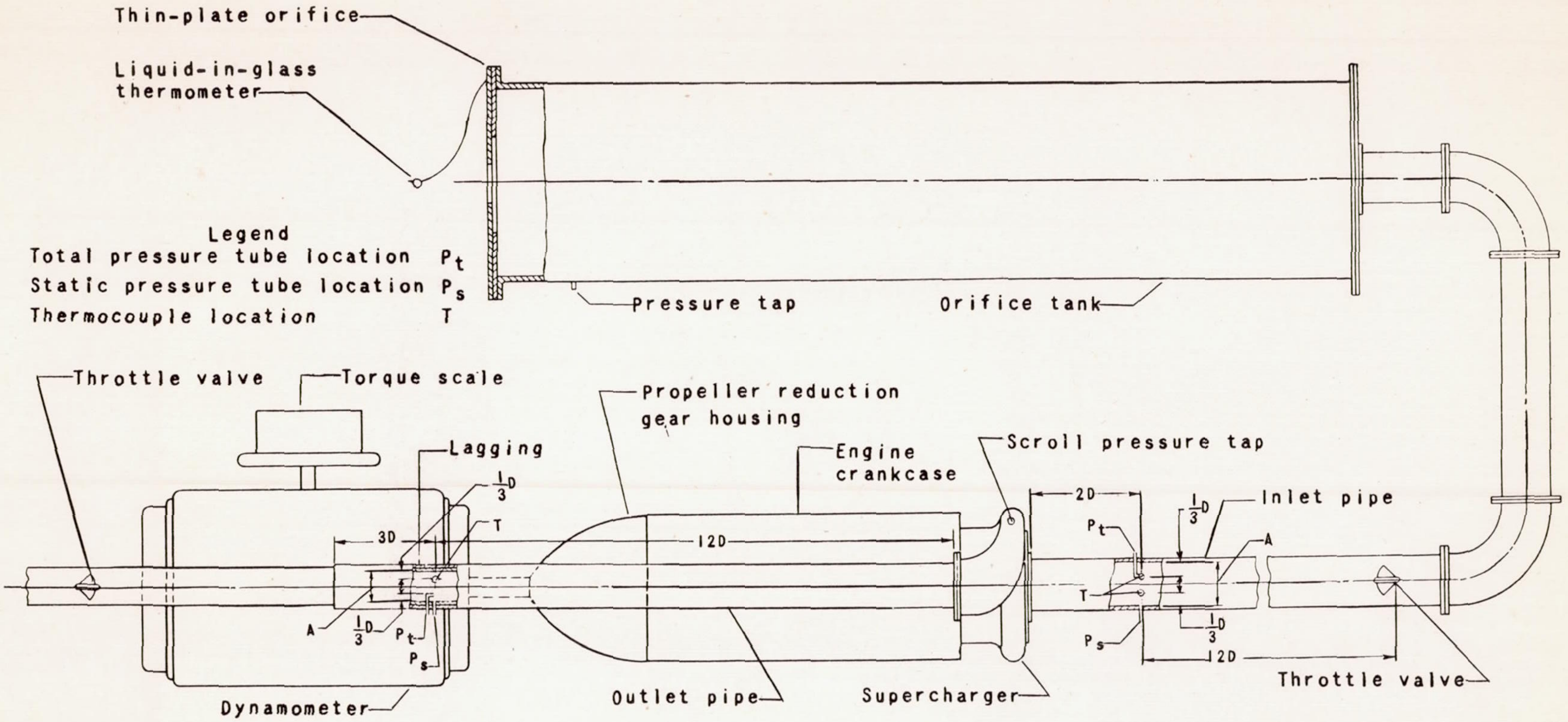


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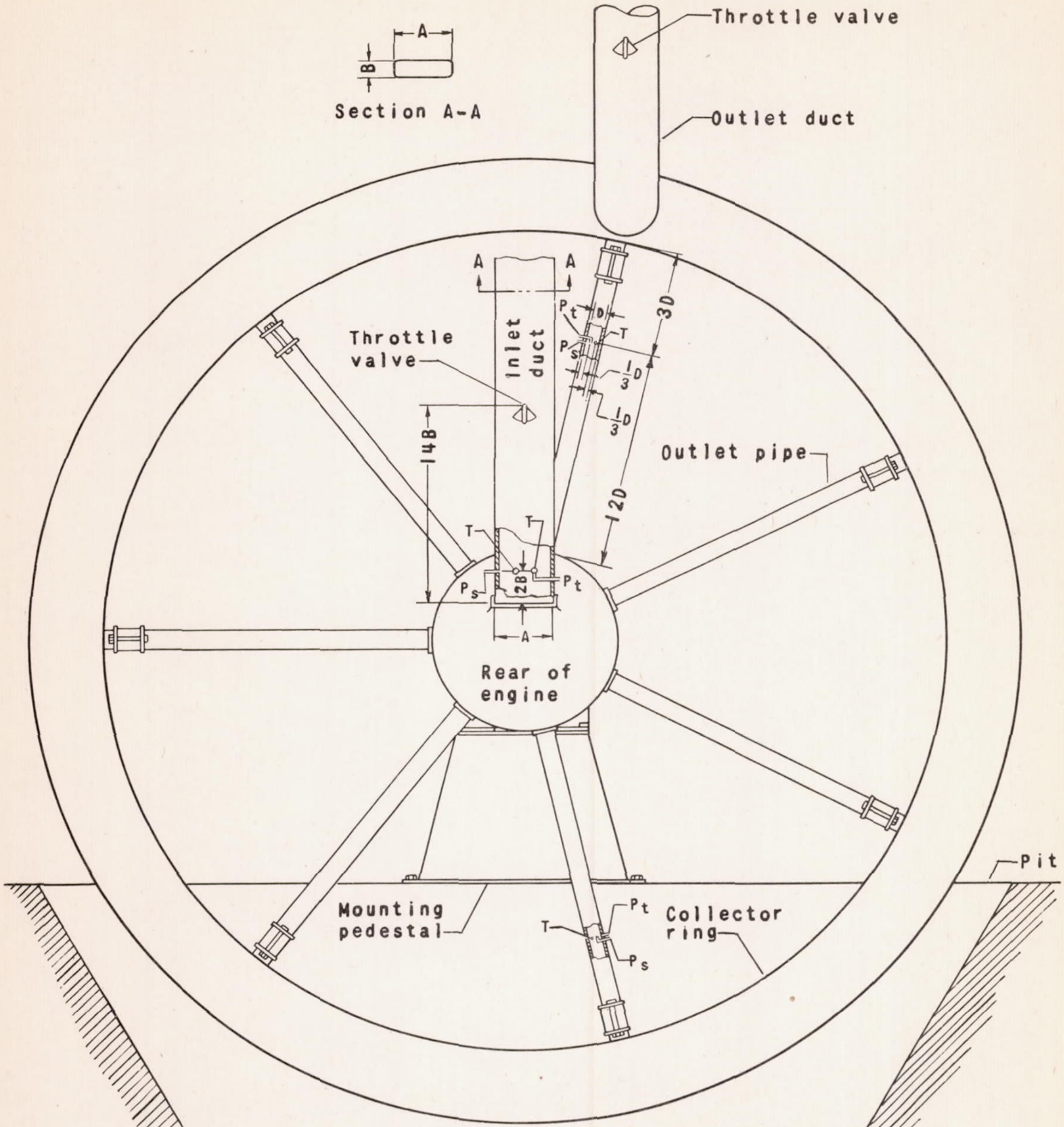
Figure 2. - Supercharger test rig for in-line engine.




Legend

| | |
|---|---|
| Total pressure tube location | $P_t$ |
| Static pressure tube location | $P_s$ |
| Thermocouple location | T |

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Figure 3. - Supercharger test rig for radial engine.

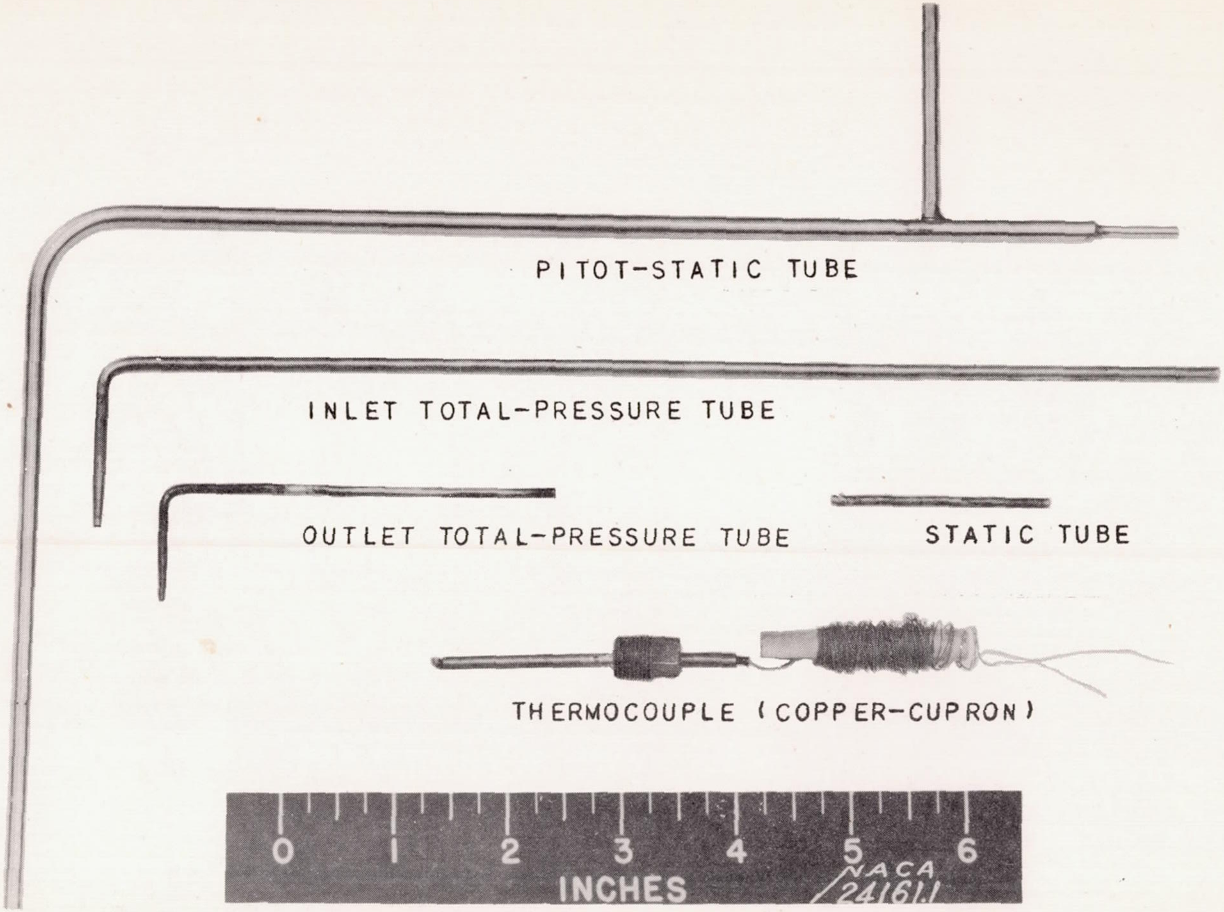


Figure 4. - Pressure tubes and thermocouple in general use.